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PERSPECTIVE

Opportunities and Challenges of DNA Materials toward Sustainable Development Goals

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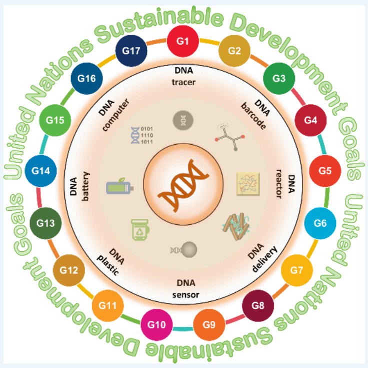

ABSTRACT: **Sustainable development represents a significant and pressing challenge confronting the global community at present. A wide variety of macroscopic engineering systems has been developed to promote sustainable development. Recent advancements in DNA materials have showcased their substantial contributions toward achieving sustainable development goals (SDGs). Compared to nonbiological materials, DNA materials possess exceptional properties such as genetic functionality, molecular programmability, recognition capabilities, and biocompatibility. These unique characteristics enable DNA materials to serve as general and versatile substrates beyond their genetic role. Consequently, they can be used to develop DNA-based engineering systems that offer versatile solutions to support sustainable development. In this Perspective, we critically examine the opportunities that DNA-based engineering systems present in contributing to the achievement of the SDGs within various real-world scenarios. We establish direct relationships between DNA-based engineering systems and the SDGs, highlighting their inherent merits in accelerating sustainable development. Furthermore, in order to successfully achieve SDGs, we address the challenges associated with these systems and emphasize the urgent need for developing multifunctional, reliable, biosafe, and intelligent DNA-based engineering systems to overcome these challenges.**

KEYWORDS: *DNA nanostructures, DNA materials, nanomaterials, biotechnology, sustainability*

INTRODUCTION

To secure the rights and well-being of everyone on a healthy, thriving planet, the 193 member states of the United Nations (UN) adopted a new 2030 Agenda for Sustainable Development on September 5, 2015. This agenda, which succeeds the UN's Millennium Development Goals, features 17 Sustainable Development Goals (SDGs) with 169 specific targets.[1,2] The SDGs aim to comprehensively address developmental challenges across social, economic, and environmental dimensions from 2015 to 2030, redirecting toward a path of sustainable development. Motivated by the SDGs, numerous engineering systems have been developed to accelerate sustainable goals. These engineering systems include green energy, seawater desalination, degradable plastics, digital twins, remediation of degraded soil, water-saving irrigation, etc., and have so far achieved remarkable progress in enhancing environmental sustainability.[3−6] Progress toward the SDGs has also been quantitatively monitored via an SDG index.[7,8] However, the latest (from 2023) global-level data and assessments presented in Figure 1 reveal that progress on half of the evaluated 140 SDG targets is weak and insufficient and that approximately 30% of these targets have not made any progress or, even more alarmingly, have regressed below their 2015 baseline levels.[9] With the 2030 deadline approaching, urgent and concerted efforts are needed to fully realize the SDGs, which require international collaboration for more effective strategies.

In recent years, with the rapid progress in nanoscience and nanotechnology, DNA nanostructures, and especially DNA materials, have been leveraged to provide promising strategies for achieving environmental sustainability from new perspectives and scales.[10−12] Since Seeman's first demonstration of artificial DNA nanostructures in 1982,[13] DNA, the central genetic materials in biological systems, has also served as a versatile nanomaterial building block. It provides a natural bridge between nanotechnology and biotechnology and creates a transformative linkage from the nanoscale to the macro-

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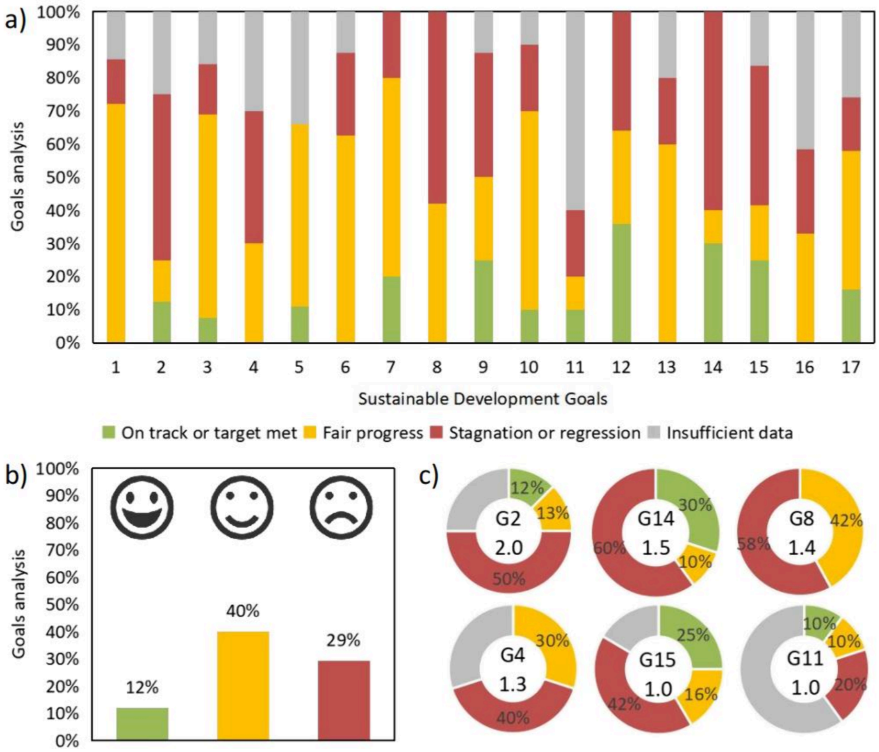

Figure 1. 2023 global-level data and assessments of SDGs. (a) Progress assessment for the 17 SDGs based on assessed targets, 2023 or latest data (percentage); (b) mean value of three progress types (on track or target met, fair progress and stagnation or regression) for 17 SDGs; (c) six goals (G2, G14, G8, G4, G15, and G11) that are currently making the slowest progress. The value at the center of the circle is the hysteresis index—red percentage/(yellow percentage + green percentage). We have only calculated the reported data here, and the insufficient data have not been included.[9]

scale.[14,15] DNA comprises a phosphate deoxyribose backbone and four bases: adenine, guanine, cytosine, and thymine encode genetic information through their sequence. The biological functionality, nanoscale geometry, biocompatibility, biodegradability, and molecular recognition capacity of DNA make it a robust candidate for constructing DNA-based engineering systems.[16,17] DNA is an amazing polymer that can be synthesized, manipulated, and modified by a vast array of well-established molecular biology tools, including enzymes.[18] Numerous DNA-based engineering systems, including DNA tracer, DNA barcode, DNA sensor, DNA plastic, DNA switch, and DNA battery, have been engineered with desired shapes and sizes, relying primarily on the classic Watson−Crick base-pairing rules for molecular self-assembly.[19−26] In support of specific targets for the SDGs, such as pollution source tracing, pathogen detection, and vaccine production, DNA-based engineering systems have demonstrated their promising and unrivaled potential.[27−29]

Despite their growing potential, DNA-based engineering systems have not been critically reviewed in real-world applications concerning the global sustainability agenda of the SDGs. As carriers of genetic information at the nanoscale, the underlying mechanisms and technical approaches that enable DNA-based engineering systems to play a productive role in enhancing environmental sustainability warrant examination. The relationship between the development and applications of DNA-based engineering systems and the achievement of the SDGs remain uncertain. Therefore, we need to provide clear and convincing evidence of how DNA-based engineering systems are directly related to the context of environmental sustainability and how they can contribute to the SDGs.

In this Perspective, we aim to bridge these knowledge gaps by explaining the underlying mechanisms and technical approaches of DNA-based engineering systems in promoting environmental sustainability. We comprehensively and critically review the types and functional characteristics of each DNA-based engineering system to establish its direct relationship with the SDGs. Building on this, we further highlight and discuss the merits and challenges of utilizing DNA-based engineering systems to achieve the SDGs. Finally, we propose strategies to overcome these challenges and offer insights into the future direction of DNA-based engineering systems in the pursuit of the SDGs.

UNDERLYING CAPABILITY AND APPROACHES OF DNA-BASED ENGINEERING SYSTEMS TO THE SDGS

Since the discovery of the double helix structure of DNA, DNA has been engineered as a general material with unique and sometimes unexpected functionalities. The underlying capability of DNA-based engineering systems to contribute the SDGs lies in the nanoscale controllability, programmability, and biocompatibility of their nanostructures, along with their self-assembly property.[10,30,31] For example, due to the nanoscale controllability and programmability, DNA nucleotide sequences can be artificially designed as specific tracers that stand out against environmental background signatures, thus aiding to identify sources of water pollution.[27] The self-assembly property of DNA allows DNA molecules to precisely form into a dendrimer-like nanostructure with specific molecular recognition probes, thus producing biometric barcodes that can simultaneously detect the DNA of multiple pathogens.[28]

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ACS Nano XXXX, XXX, XXX−XXX

Table 1. DNA-Based Engineering Systems and Their Direct Relationships to SDGs[a]

DNA-based engineering systems				SDGs	
Type	Composition	Functions	Level	Goal	Specific targets
DNA tracer	DNA, silica, polylactic acid, etc.	Identify the potential sources of pollutants in water, soil, and air[27,66−68]	Good	G6	6.3 (●●●); 6.6 (●●)
				G11	11.6 (●●)
				G14	14.1 (●●●)
DNA barcode	DNA, fluorescence dye, probe, etc.	Detect pathogens, biological species, and genetic diversity[28,37−39]	Excellent	G3	3.3 (●●●●)
				G6	6.3 (●●●)
				G15	15.4 (●●●●); 15.8 (●●●)
DNA sensor	DNA, quantum dots, electrochemical transducers, etc	Detect diseases, environmental pollutants and pathogens[40−42]	Excellent	G3	3.3 (●●●●)
				G6	6.3 (●●●); 6.6 (●●)
DNA reactor	DNA, gene, enzyme, ATP, etc.	Produce protein and vaccine[29,43−45]	Excellent	G3	3.3 (●●●●); 3.4 (●●●●); 3.9 (●●●); 3.b (●●●●)
DNA delivery	DNA, polylactic acid, enzyme, etc	Produce biodegradable capsules for wrapping drugs[17,46−48]	Excellent	G3	3.3 (●●●); 3.4 (●●●●); 3.9 (●●●)
DNA switch	DNA, probe, enzyme, etc.	Control drug release, gene expression and detection[19,49,58]	Good	G3	3.3 (●●●); 3.4 (●●●●); 3.9 (●●●)
DNA plastic	DNA, enzyme, etc.	Produce biodegradable plastic and membrane products[20,50,57]	Developing	G9	9.4 (●)
				G11	11.6 (●●)
				G12	12.5 (●●●); 12.a (●●)
				G14	14.1 (●●)
DNA battery	DNA, enzyme, lactate, protein, etc.	Provide greener and safer power without causing pollution[51,52,55,119,120]	Good	G6	6.3 (●●●)
				G7	7.a (●●)
				G11	11.6 (●●)
				G14	14.1 (●●)
DNA storage	DNA, enzyme, storage carrier, etc.	Store and read digital information[59−63]	Good	G9	9.c (●●●)
				G17	17.8 (●●●)
DNA computer	DNA, enzyme, etc.	Perform calculation programs through biochemical reactions[21,53,54,56,64,65]	Developing	G9	9.c (●●)
				G17	17.8 (●)

[a]●●●●, fully supported, achieving extensive applications; ●●●, strongly supported, achieving a large number of applications; ●●, moderately supported, achieving a moderate number of applications; ●, partially supported, achieving limited applications. Goals: G3, good health and well-being; G6, clean water and sanitation; G7, affordable and clean energy; G9, industry, innovation and infrastructure; G11, sustainable cities and communities; G12, sustainable consumption and production; G14, life below water; G15, life on land; G17, partnerships for the goals. Details for specific targets can be found on the Web site https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

Table 2. Comparison of Typical Properties between DNA Materials and Traditional Materials[a]

Property	DNA materials (e.g., DNA hydrogen)	Plastics (e.g., PE)	Metals (e.g., iron)	Ceramics (e.g., aluminum oxide)
Production cost	High	Low	Low	Low
Designability	Extremely high	High	Moderate	Moderate
Biocompatibility	Extremely high	Moderate	Low	Moderate
Mechanical strength	Low	Moderate	Extremely high	High but fragile
Degradation	On the scale of days to weeks	On the scale of decades to centuries	Nondegradable	Nondegradable
Renewability	High	Extremely high	High	Low
Environmental toxicity	Gene pollution risk	Microplastic pollution risk	Heavy metal pollution risk	Low pollution risk
Application scenarios	Biosensors, drug delivery, etc.	Packaging, consumer goods, etc.	Construction, electronics, etc.	Consumer goods, decoration materials, etc.

[a]The data listed in the table are compared under consistent conditions. Specifically, production costs are estimated based on sourcing materials of equivalent quality, and degradation times are evaluated under identical environmental conditions.

In addition to these capabilities, three technical approaches enable nanoscale DNA materials to have tremendous amplification power at the macroscale: Numerous biochemical methods for DNA functionalization including enzymes, flexible manipulations of DNA nanostructures such as DNA folding (DNA origami), and exponential chain reactions of DNA molecules including rolling circle amplification (RCA).[18,32−34] These tools and techniques allow for the precise design of DNA sequences and facilitate DNA molecules to be connected and grow exponentially, effectively enhancing the detection sensitivity, while at the same time enabling the mass production of DNA materials. For example, X-shaped DNA with a linearized gene can be cross-linked via enzymes to form gels with pores and channels; these gels have been employed to produce proteins in a cell-free fashion with high efficiency.[35] RCA can generate an elongated single-stranded DNA with millions of copies of targeted sequences via continuous enzymatic polymerization from a circular template.[36] Additionally, DNA can be easily conjugated with active functional groups, enabling the creation of a variety of DNA-based engineering systems with unprecedented properties, such as enhanced detection sensitivities.

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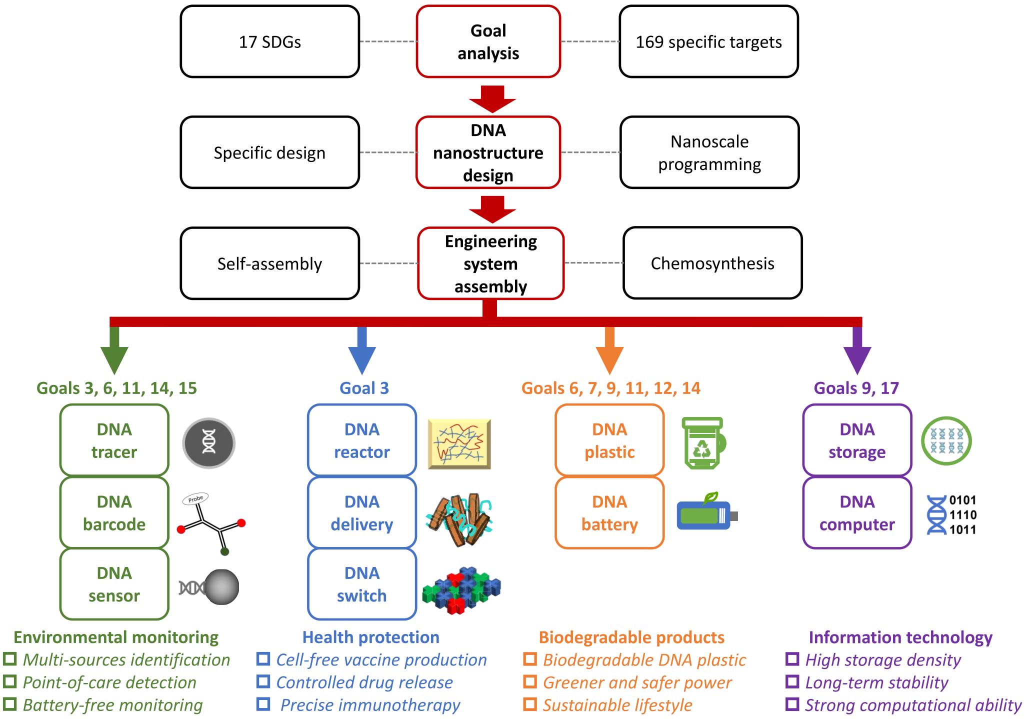

Figure 2. Workflow of constructing DNA-based engineering systems for real-world applications.

The life cycle of both DNA materials and traditional engineering materials in the context of achieving SDGs typically comprises five stages: raw materials, materials design, product manufacturing, product use, and end of life. However, there are notable disparities in these stages across the different systems. For instance, solar energy systems are primarily designed with high conversion efficiency solar panels, whereas seawater desalination systems are engineered with proficient salt ion filtration mechanisms. DNA-based engineering systems possess distinct functionalities, mainly achieved by designing the molecular structure and sequence composition of DNA to attain specific objectives, such as rapid detection of waterborne pathogens, information storage, drug delivery, etc. The well-established traditional engineering systems undoubtedly play a pivotal role in achieving the SDGs. Meanwhile, DNA-based engineering systems, as specialized systems, serve as potent adjuncts and exert an efficacious influence in specific domains.

A number of DNA-based engineering systems have been developed, including DNA tracer, DNA barcode, DNA sensor, DNA reactor, DNA delivery, DNA switch, DNA plastic, DNA battery, DNA storage, and DNA computer, all contributing to progress toward the SDGs.[17,19−21,27−29,37−68] Here, we comprehensively review the majority of DNA-based engineering systems to determine their direct relationships with the 17 SDGs. Table 1 summarizes the structural composition and functional mechanism of each DNA-based engineering system along with their respective support levels for specific targets of the SDGs. Furthermore, we conducted a comparative analysis of the physicochemical and environmental properties between DNA materials and traditional materials (e.g., plastics, metals, and ceramics) under standardized conditions (Table 2). The results demonstrate the distinct advantages of DNA materials in **molecular programmability** (sequence-directed functionality), **biocompatibility** (minimal cytotoxicity), and **controllable degradation kinetics** (enzyme-responsive breakdown), positioning them as sustainable alternatives for applications in precision medicine, biosensing, and green nanotechnology. Certain properties, such as production cost and environmental toxicity, exhibit limitations that necessitate comprehensive optimization and rigorous evaluation to achieve enhanced sustainability.

MERITS OF USING DNA-BASED ENGINEERING SYSTEMS TO ACHIEVE THE SDGS

Based on the attributes of DNA-based engineering systems and considering their potential to realize the SDGs, we highlight the merits of the following four SDG categories: (1) environmental monitoring, (2) health protection, (3) biodegradable products, and (4) information technology. The workflow of constructing DNA-based engineering systems for real-world applications, including environmental monitoring, health protection, biodegradable products, and information technology, is illustrated in Figure 2.

Environmental Monitoring. Rapid population growth and urbanization, climate change, decreasing biodiversity, water pollution, and land degradation all contribute to environmental uncertainty and pollution risk, slowing or even preventing the realization of SDGs.[69−71] Timely and accurate monitoring of environmental changes is a major challenge. DNA tracer, DNA barcode, and DNA sensor provide reliable support for achieving goals 3, 6, 11, 14, and 15 with specific targets of 3.3, 6.3, 6.6, 11.6, 14.1, 15.4, and 15.8, via their powerful multiplexed sensing, point-of-care detection, and programmable molecular recognition.

For example, the characteristics of DNA tracer, such as high specificity, unlimited coding capacity, and extreme sensitivity, enable the identification of the source of pollutants from multiple potential sites,[27] providing a prerequisite for the accurate elimination of environmental pollution and effective ecological environment restoration (toward specific targets 6.3 and 6.6). Accurately determining the source of pollution can also help decrease the negative environmental impact of cities and reduce various types of marine pollution caused by land-based activities (toward specific targets 11.6 and 14.1). It is important to note that when DNA is utilized as a tracer, it will directly encounter specific environmental conditions, such as ions, pH levels, and solvents. This inevitably has a detrimental impact on its integrity and stability and consequently affects its functionality. Therefore, in such cases, it is generally necessary to encapsulate the DNA molecules in specialized protective materials (such as polylactic acid or silica) to prevent direct contact with the environment and ensure their functionality to achieve specific targets.[23] Similarly, DNA barcode offers a great number of DNA recognition probes to reduce uncaptured signals, which is a highly effective tool to accurately detect and quickly track biodiversity,[37,72] thereby protecting endangered species and preventing invasive species (toward specific targets 15.4 and 15.8).

In addition, point-of-care detecting devices based on DNA barcode and DNA sensor enable flexible encoding schemes for multiplex assays; they can be applied to simultaneously detect multiple pathogens *in situ* in resource-limited settings.[28,73] This would greatly improve medical efficacies and sanitation conditions in developing countries and regions, enabling their ability to combat hepatitis, water-borne diseases, and other infectious diseases (toward specific target 3.3). Thus, contaminated water can be monitored in a timely manner and given priority attention, which would facilitate water pollution control and optimize water and sanitation management (toward specific targets 6.3 and 6.6).

Health Protection. The inability to prevent and treat diseases is a major obstacle to sustainable development, especially in developing countries. The most evident example is the COVID-19 pandemic in 2019, which infected hundreds of millions and caused millions of deaths. During this time, people addressed the crisis through enforced quarantine.[74] Therefore, there is an urgent need for immediate responsive capabilities to emerging pandemic diseases, including those of COVID-19. DNA reactor, DNA delivery, and DNA switch significantly facilitate the realization of goal 3 with specific targets of 3.3, 3.4, 3.8, 3.9, and 3.b via their cell-free protein production manner and controllable drug release ability.

In fact, the aforementioned DNA-based engineering systems are mainly DNA hydrogels that can be designed through manipulation of DNA sequences and then prepared by enzyme-assisted amplification reactions including RCA.[32,34] DNA reactor can realize more efficient protein and vaccine production in a cell-free manner because of enhanced gene stability and template concentration, as well as fast enzyme turnover rates.[35] This enables the rapid production of vaccines against the spread of emerging pathogens (toward specific targets 3.3, 3.4, and 3.9). An efficient vaccine production procedure could reduce drug manufacturing costs, thereby ensuring that people have access to affordable drugs and vaccines (toward specific targets 3.8 and 3.b).

Alternatively, DNA delivery and DNA switch can achieve efficient drug delivery and controlled release because drugs can be encapsulated in the liquid phase, avoiding the drug-loading step and denaturing conditions,[19,75,76] ensuring sufficient drug potency to improve the effectiveness of treatment (toward specific targets 3.3 and 3.4). Especially, they can enable efficient co-delivery of DNA drugs, tracer dyes, and siRNA for synergetic therapy. For example, DNA delivery was encapsulated with the anticancer agent doxorubicin along with a specific immune stimulant, cytosine−phosphate−guanine (CpG) motif. In this scheme, doxorubicin was released to directly kill cancer cells, and the CpG motif elicited immunostimulatory signals to produce tumor necrosis factor.[77] Using this robust drug delivery strategy, undoubtedly, it is beneficial for reducing the number of deaths and illnesses caused by hazardous chemicals or environmental pollution (toward specific target 3.9).

Biodegradable Products. With the increasing production and consumption of petroleum and its derivatives, plastic waste and pollution have become a major environmental problem. The need for the harmless disposal of plastics and the use of clean energy is becoming more urgent.[78,79] DNA plastic and DNA battery offer alternative solutions to the SDGs 6, 7, 9, 11, 12, and 14 with specific targets of 6.3, 7.a, 9.4, 11.6, 12.5, 12.a, and 14.1, via their recyclable ability and greener and safer electricity supply.

As a bio-macromolecule, DNA's inherent environmental friendliness lends itself well in real-world applications. For example, natural biomass DNA or biomass-derived ionomers have been used to create various biodegradable DNA plastic products; they have been designed to form products such as disposable utensils, toys, cups, and membranes.[20,50] While these DNA-based plastic products are not yet available on the consumer market, they clearly present a promising step forward to an environmentally friendly lifestyle, reducing both land-based plastic waste and pollution on the marine environment (toward specific targets 9.4, 11.6, and 12.5). Moreover, biomass DNA could be sourced from abundant, renewable supplies such as algae or waste straw, realizing an efficient, green, and value-added use of biomass resources; this lays the groundwork for more sustainable production and consumption patterns (toward specific target 12.a).

On the other hand, bio-electrocatalysis is regarded as a green and efficient method to produce clean biofuels. The incorporation of DNA materials to bio-electrocatalytic electrodes for enzyme immobilization has been reported in the construction of enzymatic biobatteries.[51,55,80] DNA-based biobatteries, composed of DNA, enzymes, lactate, protein, and water, have the potential to achieve higher catalyst densities, providing greener and safer power with harmless degraded products that are beneficial for a sustainable lifestyle (toward specific target 7.a). For example, redox DNA hydrogels were used to replace redox polymer hydrogels for self-exchange-mediated bio-electrocatalytic application.[81] The findings demonstrated that the current density from the electrocatalytic oxidation of NADH at the TBO/DNA/TP electrode (65 μA/cm^2) is 4-fold higher than that obtained at the TBO/TP electrode (16 μA/cm^2). The partial replacement of traditional energy sources, including chemical batteries, with greener DNA-based biobatteries could decrease waste generation and its potential adverse impact on the marine environment (toward specific targets 6.3, 11.6, and 14.1).

Information Technology. With the explosive increase in human knowledge, especially the development of artificial intelligence technology, there is a need for efficient storage of vast amounts of information and the execution of increasingly complex computations.[82,83] This poses challenges for existing information storage and computing. DNA storage and DNA computer can offer effective strategies to address SDGs 9 and 17 with specific targets of 9.c and 17.8, through their outstanding information storage and computing capabilities.

The high density and information quality, long-term stability, low maintenance cost, and other excellent characteristics have

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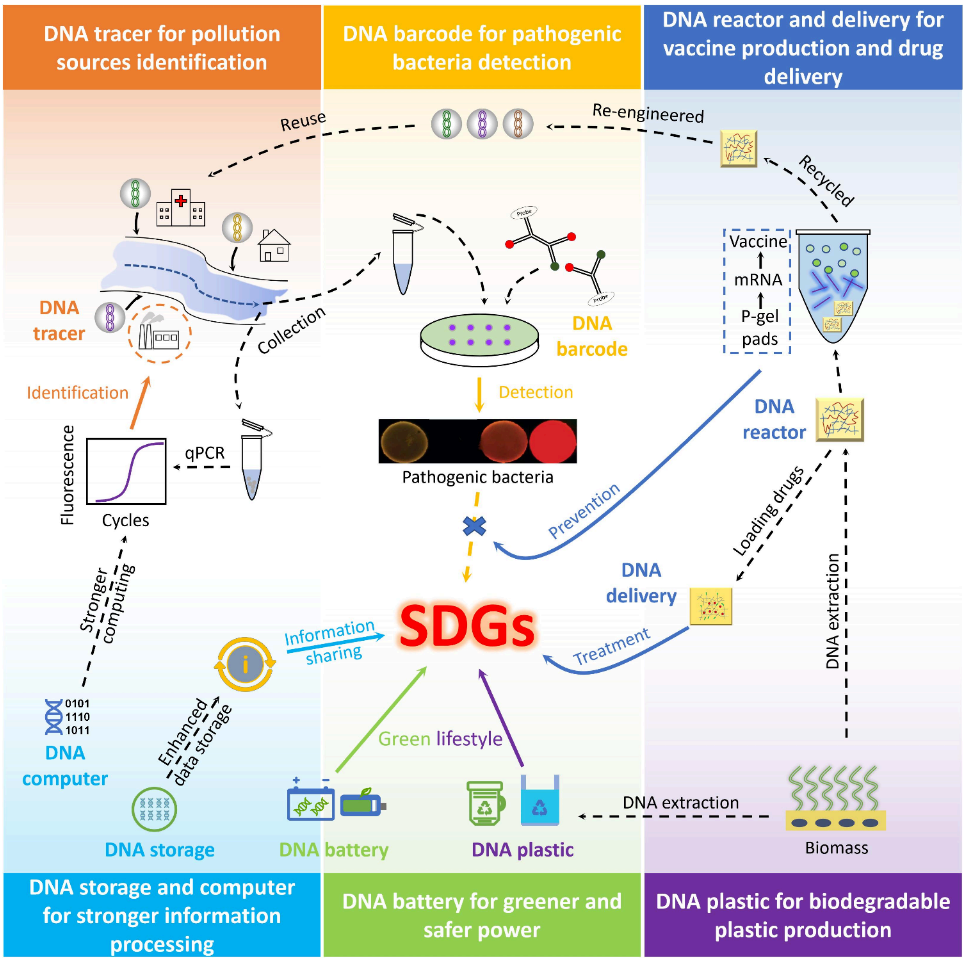

Figure 3. Robust strategy of integrating various DNA-based engineering systems to achieve the SDGs. Reprinted with permission from ref 12. Copyright 2020 Elsevier.

made DNA molecules an attractive alternative for digital information storage.[59,60] The process of DNA storage begins by converting binary digital information into a sequence of the four nucleotide bases (A, C, G, and T); this sequence is then chemically synthesized and stored as DNA molecules.[61,62] For example, ten digital pictures of Dunhuang murals, comprising a 6.8 MB zipped file, were recorded through oligo synthesis, resulting in the generation of an ssDNA "Master Pool" containing 210000 unique ssDNA strands.[63] The information storage density of DNA can reach 10^{19} bits/cm^3, which is 10^6 times that of a hard drive. Theoretically, the world's storage needs could be met with about a kilogram of DNA.[84] This would contribute to reducing the cost of information storage based on traditional methods such as solid-state drives and mechanical hard drives, thereby enhancing the accessibility of information storage and enabling the provision of information services to the developed countries at affordable prices (toward specific targets of 9.c and 17.8).

Additionally, the advent of DNA computer has provided a new way to process information and carry out calculations.[21,53,64] DNA computers are not the type of computers we use in our daily lives. Instead, it is incredibly compact, with the capacity to fit an enormous number of computing units within a mere 1.5 mL test tube. Utilizing the information-processing capabilities of biological molecules, DNA computation replaces the switching components of traditional digital circuits, enabling them to perform a staggering one billion calculations per second.[85] In recent studies, researchers have successfully utilized single-stranded oligonucleotides to create large-scale DNA integrated circuits for general-purpose computing without apparent signal attenuation.[65] They developed DNA-based programmable gate arrays (DPGAs) and demonstrated their integration with an analog-to-digital converter, enabling the classification of disease-related micro-RNAs. Although DNA computer has not yet been put into commercial applications, their potential in complex data computing and information processing would contribute to the development of information technology (toward specific targets of 9.c and 17.8).

CHALLENGES AND STRATEGIES

While DNA-based engineering systems offer significant potential for achieving the SDGs, they are not a universally applicable solution. These systems have distinct advantages in accomplishing specific technical goals, such as goals 3, 6, and 9. However, they may be less effective in addressing certain macroscale goals, such as goals 5, 8, and 10. Furthermore, the challenges in mass-producing specific DNA have hindered progress in realizing the specific targets of the SDGs, particularly in real-world applications that require large quantities of DNA. Additionally, the biosafety implications of large-scale DNA applications may raise public concerns, necessitating the development of response strategies to address them. Lastly,

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ACS Nano XXXX, XXX, XXX−XXX

the knowledge gaps between disciplines present significant obstacles for scholars from different fields in designing the DNA-based engineering systems that they require.

Macroscale Goals Realization. A scaling limitation has been widely observed in approaches to achieve the sustainable goals.[86−90] In this Perspective, DNA-based engineering systems can directly contribute to goals 3, 6, 9, 11, and 14, which are often achieved through technological advancements at a microscale level. However, DNA-based engineering systems are not directly applicable to goals 1, 2, 4, 5, 8, 10, 13, and 16, which usually necessitate adjustments and optimization of social institutions and policies at a macroscale level, in addition to technological advancements.

To achieve the macroscale SDGs, DNA-based engineering systems need to be up-scaled from the microscale. In this case, in addition to selecting the appropriate DNA-based engineering systems to achieve the specific targets, system integration approaches that incorporate various components across different dimensions or scales have been recognized as effective in transitioning from single-goal realization to multigoal realization.[91,92] These approaches help address scaling limitations to some extent.

The integration of DNA-based engineering systems generates synergistic effects that facilitate the simultaneous achievement of multiple specific targets, thereby overcoming macroscale challenges (Figure 3). This strategy resembles nexus approaches that promote integrated planning and management.[93−95] For example, a multifunctional system that combines DNA tracer, DNA barcode, DNA reactor, and DNA delivery can provide a synergistic solution for pollution source identification, bacteria detection, and vaccine production.[12] Such an integrated system could be implemented flexibly and cost-effectively to improve health and sanitary conditions in low-income countries. This, in turn, can enhance their labor capacity, provide access to more equitable employment opportunities, and foster national development.

Developing an integrated system should be based on a rational design rather than arbitrary combinations. The nanoscale controllability, specificity, and biocompatibility of DNA materials enable different engineering systems to be distinct yet intricately connected, showcasing the versatility and complexity of DNA materials in various applications.[30,96] The integration strategy should include not only DNA-based engineering systems but also other biocompatible materials, such as gold nanoparticles, clay, glycerol, quantum dots, and ionomers, to form integrated and synergistic composite systems.

Adequate Quantity. Achieving specific objectives, such as the production of biodegradable plastics and information storage for environmental and industrial applications, necessitates a substantial supply of DNA substrates. Despite their significant potential to advance SDGs, DNA materials remain in their nascent stage with limited commercial infrastructure. Consequently, the development of DNA-based engineering systems currently incurs substantial costs, primarily due to the technical challenges and energy-intensive processes associated with high-purity DNA extraction and enzymatic synthesis. Therefore, a major challenge lies in establishing cost-effective, scalable production methods for DNA-based engineering systems, as their commercial viability hinges on resolving this supply demand imbalance.

Emerging studies demonstrate that extracting DNA from abundant biomass, such as algae or agricultural waste straw, could be a sustainable and cost-effective strategy for large-scale production of DNA materials.[50,97] These biomass feedstocks are widely available as biological waste in natural and anthropogenic ecosystems, ensuring low-cost sourcing. Building upon this foundation and leveraging well-developed bioengineering techniques, such as cloning and PCR amplification, industry-scale production of DNA materials becomes feasible. For instance, plasmid DNA can be mass-produced through bacterial engineering using *Escherichia coli* (*E. coli*) as a host organism, which can subsequently be precisely engineered to generate DNA tracers for environmental tracing.[23] Moreover, it is noteworthy that DNA materials exhibit superior efficiency, enabling the achievement of desired outcomes in significantly smaller quantities. For instance, in identifying water movement pathways, the injection volume of DNA tracer is tens of thousands of times lower than that of ion or dye tracers.[98,99] This remarkable efficiency not only reduces material costs but also minimizes the environmental impact. Similarly, DNA reactors utilizing cell-free systems have demonstrated a 300-fold increase in yield compared to traditional solution-based methods.[35]

There is a critical need to broaden the practical applications of DNA-based engineering systems, stimulate growth in the consumer market, and accelerate associated technological advancements. Additionally, the UN and national governments have a responsibility to act as facilitators in establishing cross-cutting and collaborative research and development platforms. They should actively leverage financial instruments, such as innovation grants, tax incentives, and public−private partnerships (PPPs), to foster technological innovation and attract increased social capital investment in the DNA materials sector. For instance, establishing dedicated innovation funds or co-investment schemes with private stakeholders can accelerate the development of high-impact technologies, such as enzymatic DNA synthesis or DNA-based data storage systems. Such efforts will contribute to lowering raw material costs, boosting industrial output, and expanding consumer market opportunities.

Biosafety Concerns. DNA-based engineering systems, owing to their composition of synthetic nucleic acid architectures, may introduce unique complexities, including immunogenicity, risks of genetic contamination, and unintended ecological consequences. For instance, synthetic DNA constructs containing unmethylated CpG motifs may activate TLR9-mediated immune responses in mammals, potentially triggering systemic inflammation.[100] The integration of horizontally acquired DNA fragments into microbial genomes may perturb native metabolic networks, potentially reducing taxonomic and functional diversity within soil microbial communities.[101] Enhanced DNA stability coupled with measurable horizontal gene transfer has been observed in clay-rich soil environments, while the dissemination of genetic material via microplastics may globally impact aquatic ecology and evolutionary processes.[102,103]

To address these biosafety concerns, a multitiered strategy must be implemented. First, establishing causal relationships between the toxicity of DNA materials and their physicochemical properties.[104,105] This requires the development of a comprehensive material library encompassing diverse DNA architectures and their associated toxicological profiles. Second, advanced *in situ* analytical techniques are required to monitor the dynamic transformation of DNA materials in environmental and biological systems, including their degradation kinetics, horizontal gene transfer (HGT) frequencies, and interactions with microbial communities.[106,107] Third, to mitigate gene

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ACS Nano XXXX, XXX, XXX−XXX

safety risks, systematic toxicology approaches leveraging bioinformatics and multiomics technologies (e.g., genomics, transcriptomics, and metabolomics) should be actively developed.[108] These methods enable the detection of subtle molecular changes in host organisms and ecosystems, allowing for the timely optimization of DNA architecture designs. Collectively, these initiatives will enhance the risk assessment and management of DNA materials, paving the way for biocompatible and environmentally sustainable DNA-based engineering systems.

Currently, countries worldwide lack comprehensive industry regulations and legislative frameworks for products containing DNA materials. For instance, specific guidelines need to be established to govern the distribution of DNA products and evaluate their interactions with humans and ecosystems across spatial scales, using the metacoupling approach.[109] Moreover, specialized subinstitutions responsible for food safety, pharmaceutical health, environmental protection, and consumer protection should develop tailored regulatory measures and provide domain-specific guidance for DNA products within their respective jurisdictions. Finally, given the diverse applications of DNA materials, risk assessments should be conducted on a case-by-case basis, considering factors such as exposure pathways, biological interactions, and environmental persistence.

Overall, regulatory agencies should oversee the entire lifecycle of DNA materials, conducting rigorous safety evaluations at each stage—from design and production to application and disposal—and establishing comprehensive guidelines or standards to ensure safe use. We anticipate that as biosafety assessment methodologies for DNA materials continue to advance, regulation frameworks and legislation measures will be progressively strengthened, fostering the responsible development and deployment of DNA materials.

Knowledge Gap. At present, the construction and utilization of DNA-based engineering systems to achieve SDGs require strong professional knowledge and skills. This poses a major challenge for researchers in non-DNA fields who wish to apply these systems to address practical problems within their respective areas of specialization. For example, environmental engineers in hydrological monitoring might want to use DNA tracer but could lack expertise in designing DNA sequences and preparing DNA materials.

To address and bridge these knowledge gaps across various disciplines, intelligent development of DNA-based engineering systems is crucial. A viable approach is to create a versatile framework that conducts comprehensive analyses of the application requirements for achieving specific SDGs, followed by devising automatic algorithms and/or computer programs for the construction of DNA-based engineering systems.[110]

The intelligent development of DNA-based engineering systems includes several key components:[111−114] (i) establish a comprehensive database that includes a wide range of information on deoxynucleotide monomers, oligonucleotide sequences, DNA motifs, and material structures; (ii) determine the precise relationship between sequences/structures and their functions; (iii) perform intelligent analysis programs tailored to practical application scenarios.

In a typical scenario, a specific requirement is input into the analysis program, which then analyzes the functions associated with this requirement in the form of modules. These functional modules extract the necessary molecular and structural information from the established database using the sequences/structures−functions information. Ultimately, the program outputs the required DNA sequences for constructing the DNA-based engineering system, as well as the methods for assembling these sequences into materials with designated functions.[115] Moreover, this system can be integrated with artificial intelligence seamlessly. Machine learning techniques can be employed to obtain precise correlation models between DNA molecule design and actual functions.[116−118] By inputting a substantial amount of training data from practical cases, the accuracy of the model can be significantly improved.

CONCLUSION AND PROSPECTIVE

Although enormous progress has been made in demonstrating that DNA-based engineering systems are being developed to achieve the SDGs, their real-world applications remain nascent. In this Perspective, we have highlighted the underlying capacity and principal approaches of DNA-based engineering systems to fulfill the SDGs and have established a direct relationship between DNA-based engineering systems and the SDGs with specific targets. DNA-based engineering systems are potentially powerful for achieving SDGs, yet they are not a one-size-fits-all remedy. Through a comprehensive review here, we showcased the remarkable advantages and impressive benefits of using DNA-based engineering systems in environmental monitoring (goals 3, 6, 11, 14, and 15), health protection (goal 3), biodegradable products (goals 6, 7, 9, 11, 12, and 14), and information technology (goals 9 and 17). We have also pointed out the limitations of DNA-based engineering systems in achieving goals 1, 2, 4, 5, 8, 10, 13, and 16 due to scaling and quantity challenges.

In this Perspective, we further envisioned strategies to overcome the current limitations. System integration approaches could be utilized to develop multifunctional engineering systems by incorporating various DNA-based engineering systems, which could provide a synergistic solution to overcoming the scaling barrier. Innovation in DNA extraction technologies could lead to massive and cost-effective extraction of DNA from abundant biomass, including waste biomass. The risk associated with the use of DNA materials in real-world applications should be rigorously examined and assessed, necessitating the development of practical application guidelines. A high degree of collaboration between different disciplines is surely anticipated. DNA-based engineering systems need to be developed intelligently, from a goal-driven approach, providing simple and efficient preparatory pathways to bridge disciplinary gaps.

With 2030 approaching, the international community is urgently advancing efforts to improve current engineering systems to fully realize the SDGs. The unique properties of DNA materials grant DNA-based engineering systems controllability, flexibility, and adaptability, enabling them to evolve continuously and address the complex and ever-changing challenges of sustainable development. Certainly, it is important to note that in comparison to traditional materials such as plastics and metals, DNA materials currently have limited applications in the real world due to their higher production costs. Despite the availability of well-established chemical synthesis methods and biomass extraction techniques, the absolute output of this material cannot rival that of traditional materials. Consequently, DNA materials are not suitable for sustainable target areas such as the construction industry, the automotive industry, and large-scale industrial products. Rather, DNA materials are more applicable to target fields, such as biomedical engineering,

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ACS Nano XXXX, XXX, XXX−XXX

bioinformatics, and environmental monitoring, where high precision, rapid response, and precise manipulation are required. If traditional materials are regarded as the foundation for achieving SDGs, then DNA materials can be viewed as specialized adhesives within this foundation, aiding in consolidating and strengthening the structure of sustainable development. DNA materials should not be seen as replacements for traditional materials but rather as potent supplements to traditional systems, working in concert to achieve SDGs.

Notably, several DNA-based subsystems, such as DNA computer, DNA storage, DNA plastic, and DNA battery, continue to confront substantial technical bottlenecks requiring resolution. For instance, while DNA exhibits potential for ultrahigh-density data encoding and remarkable chemical stability, its technological implementation remains constrained by persistent scientific and engineering challenges, including but not limited to inefficient data transcription rates, error correction issues, and restricted accessibility. Current technological paradigms offer limited comprehensive solutions to these fundamental constraints. Critical advancements will necessitate synergistic innovations across multiple disciplines, particularly by leveraging emerging artificial intelligence technology. The integration of generative deep learning models for nucleotide sequence optimization, neural-network-guided error correction algorithms, and AI-accelerated molecular dynamics simulations may potentially overcome current limitations. Furthermore, the convergence of CRISPR-based nucleic acid editing technologies with automated robotic synthesis platforms may enable transformative breakthroughs in this domain.

With government funding and private investment supporting this field, we anticipate a proliferation of more DNA-inspired applications to enhance existing engineering systems. With ongoing advancements in nanotechnology and biotechnology, the family of DNA-based engineering systems will expand significantly, providing an excellent foundation for developing more integrated and robust engineering systems to achieve SDGs.

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Author Contributions

R.L. and D.L. designed the research. R.L. conducted the data analysis and wrote the original manuscript. R.L., D.Y., D.L., and J.L. contributed to the revision of the manuscript.

Notes

The authors declare no competing financial interest.

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ACS Nano XXXX, XXX, XXX−XXX